AD-A021 931

IMPROVED PROCEDURES FOR DETERMINING SEISMIC SOURCE DEPTH FROM DEPTH PHASE INFORMATION

Edward Page

ENSCO, Incorporated

Prepared for:

Air Force Technical Applications Center

November 1975

083128

ADA021931

IMPROVED PROCEDURES FOR ~~DETECTING~~ Determining SEISMIC SOURCE DEPTHS FROM DEPTH PHASE INFORMATION

QUARTERLY REPORT

Edward A. Page
Francis J. Cook

November 1975

Sponsored by:

Advanced Research Project Agency
ARPA Order No. 2551

APPROVED FOR PUBLIC RELEASE.
DISTRIBUTION UNLIMITED.

Notice of Disclaimer

The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency, the Air Force Technical Applications Center, or the U.S. government.

A

F-200.1473 *DD Form 1473:* Report Documentation Page

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER:
2. GOVT ACCESSION NO:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): Improved Procedures for Determining Seismic Source Depth from Depth Phase Information
5. TYPE OF REPORT & PERIOD COVERED: Quarterly Report
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Edward Page
8. CONTRACT OR GRANT NUMBER(s): F08606-76-C-0003
9. PERFORMING ORGANIZATION NAME AND ADDRESS: ENSCO, Inc. 8001 Forbes Pl., Springfield, VA.
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Nov. 1975
11. CONTROLLING OFFICE NAME AND ADDRESS: DCASD, Baltimore, Bldg. 22, Fort Holabird, Baltimore, Maryland 21219
12. REPORT DATE:
13. NUMBER OF PAGES: 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Vela Seismological Center, 312 Montgomery Street, Alexandria, Va. 22314
15. SECURITY CLASS. (of this report):
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report):

APPROVED FOR PUBLIC RELEASE

DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

Seismic Source depth, depth phase, echo detection

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

Seismic Source depth determination techniques, developed under two previous contracts, were formulated into an automated analysis procedure. Differential travel time information, for several propagation modes relevant to the analysis, have been made accessable through 3-D curve fitting.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SUBJECT: Improved Procedures for Determining Seismic Source Depths from Depth Phase Information

AFTAC Project No	VELA T/6710
ARPA Order No	2551
ARPA Program Code No	6F10
Name of Contractor	ENSCO, INC.
Contract No	F08606-76-C-0003
Effective Date of Contract	1 September 1975
Reporting Period	1 September 1975 30 November 1975
Amount of Contract	$59,998
Contract Expiration Date	30 June 1975
Project Scientist	Edward Page 703/569-9000

Introduction and Summary

During the first quarter of this contract, seismic source depth determination techniques (developed during the two previous contracts), were formulated into an automated analysis procedure. In this procedure, the source depth is determined by the degree to which cepstrum patterns, computed from different portions of multi-station data, agree with those expected for a given source depth. The variation in differential travel times caused by the location of stations and the presence of later propagation modes are both accounted for, and the depth phase information in the entire seismogram is involved in the depth estimate. The analysis procedure involves the computation of the cepstrum, cepstrum match filter outputs, stochastic averaging, and use of the differential travel time for several propagation modes. The travel time data, automatically accessed in the analysis procedure, is stored as coefficients defining a polynomial surface fitted to the three-dimensional data of travel time versus source depth and source to receiver epicenter distance.

In the current procedure, multi-channel seismic data is read in and a plot of the cumulative CMF outputs versus source depth is computed. The Illinois Event of 11/9/68 has been analyzed thus far, and the output indicates a clear detection of a 25 km source depth, correct for this event. We now discuss in more detail the analysis procedure, the computer storage of the travel time information, and the application of the seismic source depth analysis.

Major Accomplishments

1. Seismic Source Depth Analysis Procedure

The seismic source depth analysis procedure is illustrated in the flow chart of Figure 1. The seismic data recorded over a suite of stations are selected to start at the onset of the P wave. Next the data sample length, governing the maximum differential delay time observable, and the length of coda to be analyzed, are selected.

At this point, a set of consecutive data samples covering the selected coda length for each station recording has been determined. A data sample is selected and a cepstrum and cepstrum matched filter output is calculated. The procedure used to calculate the CMF is illustrated in Figure 2. The first of a range of trial source depths are then selected for the analysis. For this trial depth and station epicenter distance, the differential travel times for the following propagation modes are accessed from storage: pP-P, PP-P, pPP-PP, PPP-P, pPPP-PPP, PcP-P, pPcP-PcP. For the start and end time of the data sample, it is decided which modes will contribute to the cepstrum for this particular data sample. The maximum CMF output within a given time window of the expected time delay between the surface reflected arrival and the direct arrival for each of these propagation modes is accumulated in the output amplitude for this trial source depth. For this same sample, the procedure is repeated over the range of trial depths used. This completes the analysis of this data sample and the next data sample is likewise processed. One then plots the cumulative CMF output as a function of depth, and a peak in the distribution will indicate the depth estimate.

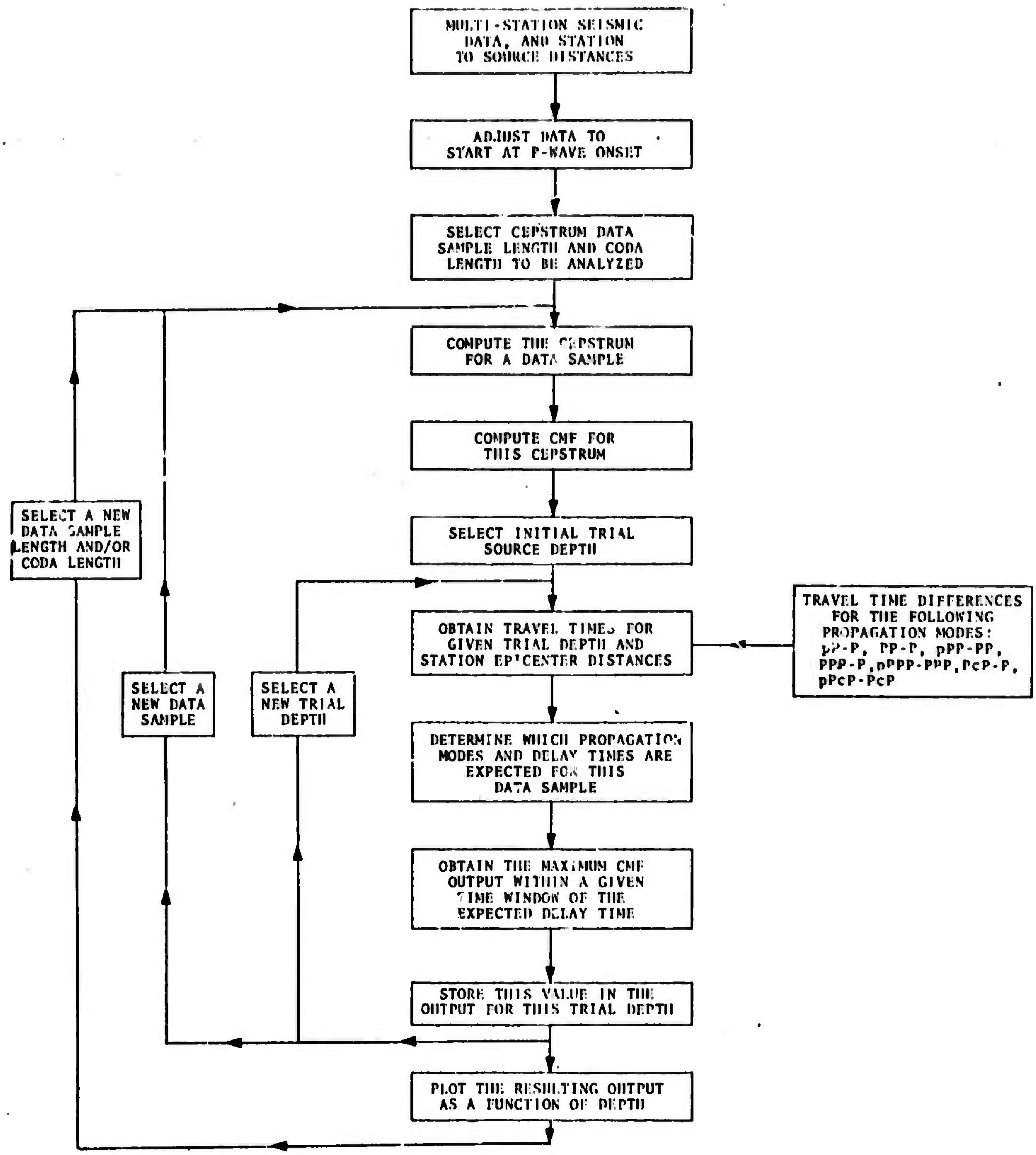

FIGURE 1. SEISMIC SOURCE DEPTH DETERMINATION PROCEDURE

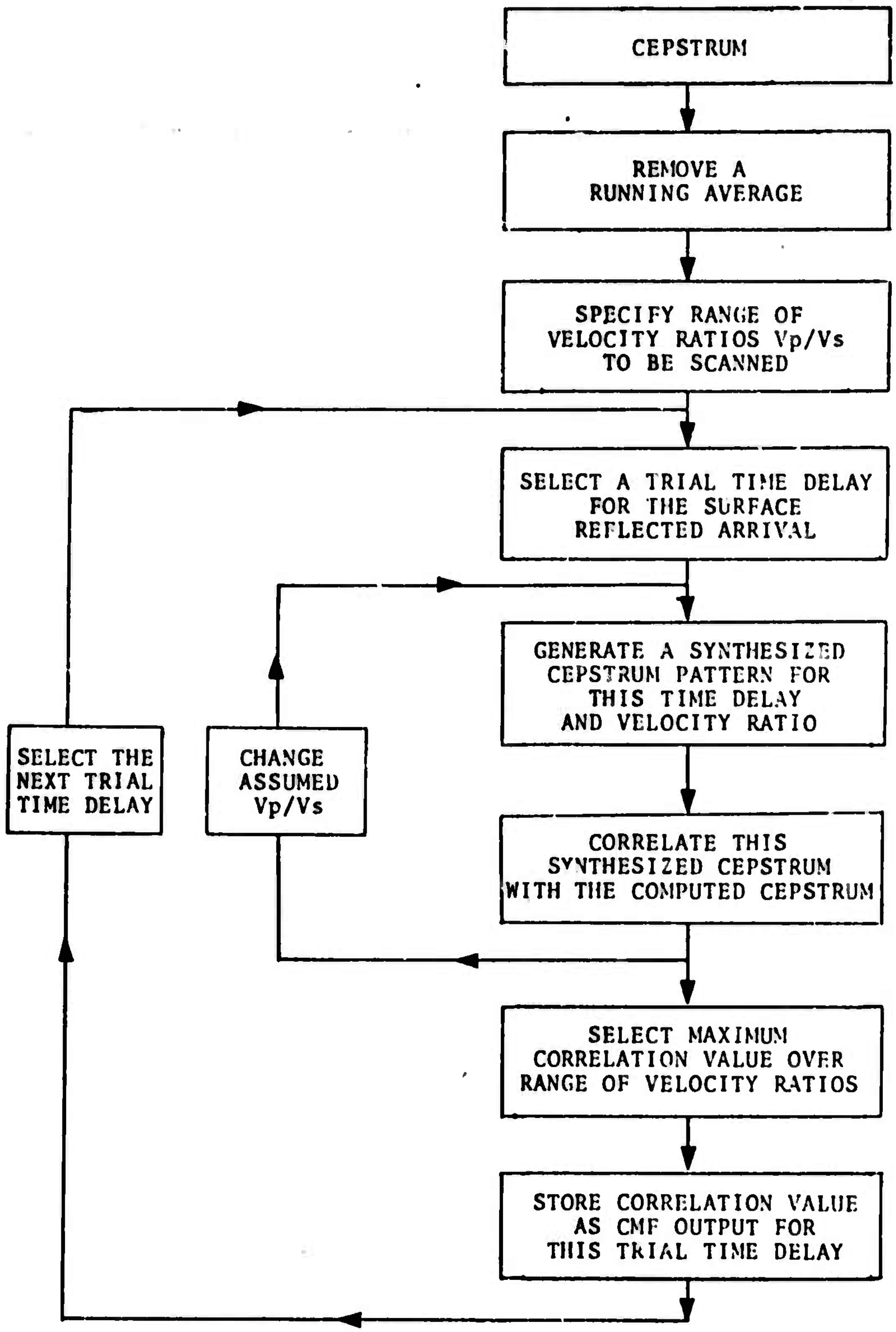

FIGURE 2. CALCULATION OF CEPSTRUM MATCHED FILTER (CMF) OUTPUT

This entire procedure is then repeated for different sample lengths and/or coda lengths.

The procedure was applied to the Illinois Event (11/9/68) using a sample length of 256 points and five consecutive coda samples for each of the six station recordings. The resulting output as a function of depth (in km) is plotted in Figure 3 and a clear detection of the 25 km source depth for the event is evident.

In the next section we discuss the techniques developed to facilitate the storage and accessing of the differential travel times used.

2. Polynomial Surface Representation of Differential Travel Times

To account for depth phase delay time variations along seismic coda, one needs access to the differential travel times for various seismic phases. From previous work, these travel time differences were obtained by the application of a ray tracing program based on the spherically symmetric isotropic earth velocity model used for the BSSA seismological tables. For this current work, an analytic three-dimensional representation of these data was developed in order to facilitate computer access and to perform the necessary interpolation of these values. We now describe the procedure for obtaining the representation of these differential travel times as a function of source depth and source to receiver distance for the following seismic propagation modes: pP-P, PP-P, pPP-PP, PPP-P, pPPP-PPP, PcP-P, pPcP-PcP.

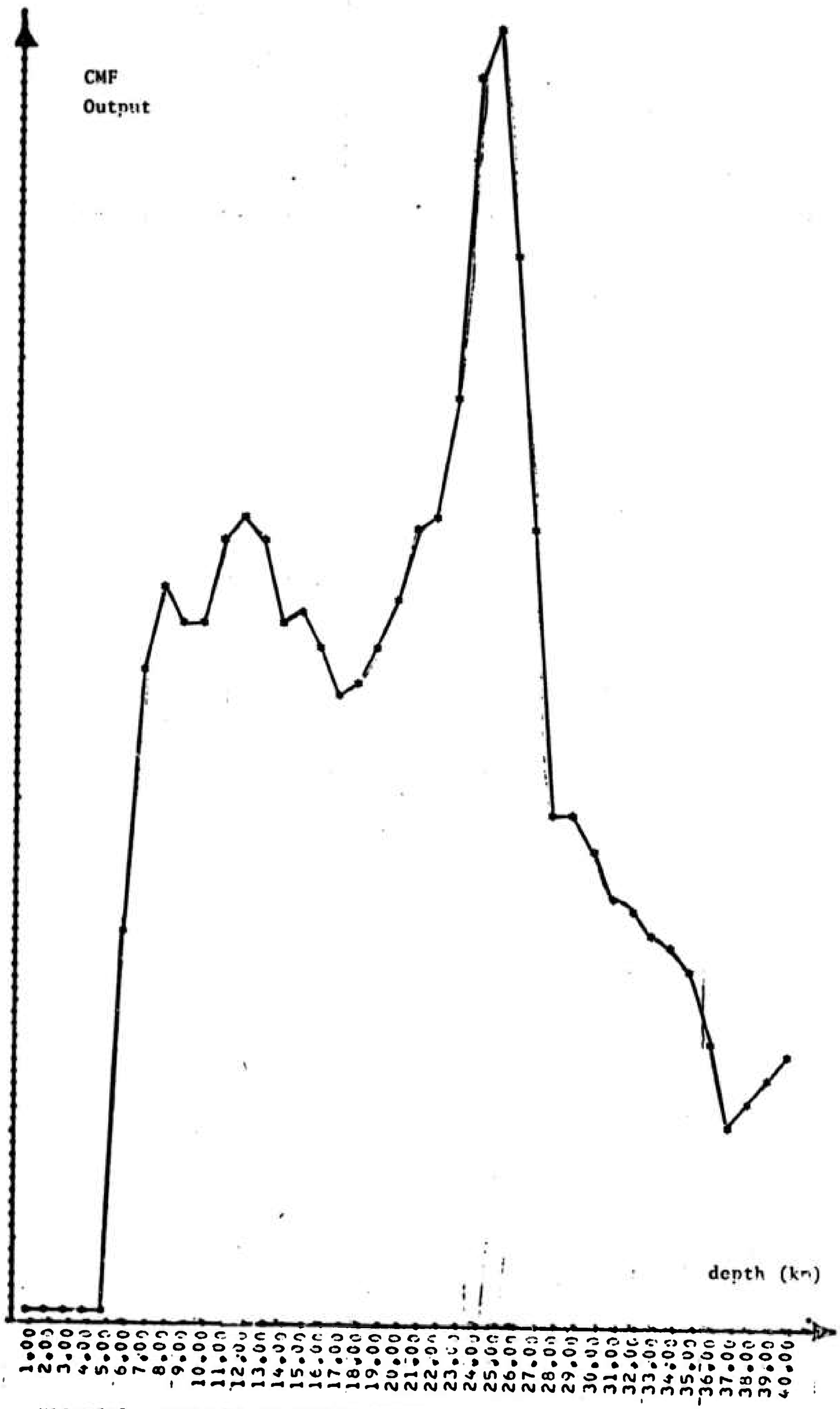

FIGURE 3. RESULTS OF SOURCE DEPTH ANALYSIS FOR ILLINOIS EVENT

Case I: Surface Fits to pP-P, pPPP-PPP, pPP-PP, pPcP-PcP

An examination of Figure 4 suggests we represent these data as a double power series in which the travel time difference τ is the dependent variable and the depth d and epicenter distances Δ are the independent variables. The surface of travel time differences is then given by

$$\tau(d,\Delta) = \sum_{ij} \tau_{ij}\Delta^j d^i$$

The coefficients τ_{ij} and the number of them needed were determined as follows. Each curve at constant Δ_c was found to be adequately represented by a cubic in d:

$$\tau(d,\Delta_c) = \tau_1(\Delta_c)d + \tau_2(\Delta_c)d^2 + \tau_3(\Delta_c)d^3$$

Here τ vanishes at zero depth. The least squares values of $\tau_i(\Delta)$ were then in turn adjusted to a power series in Δ:

$$\tau_i(\Delta) = \sum_{j=o}^{N} \tau_{ij}\Delta^j \text{ , } i=1,2,3$$

Reliable input data for Δ less than 10° were not available, so no attempt was made to force $\tau_i(\Delta)$ to vanish at zero epicenter distance. Thus, our representation should be used only for $\Delta \geq 10^\circ$. All the data sets of Case I can be represented by N=9. Examples of the effectiveness of this representation are shown in Figures 5a through 5d for pP-P, pPP-PP, pPPP-PPP, and pPcP-PcP.

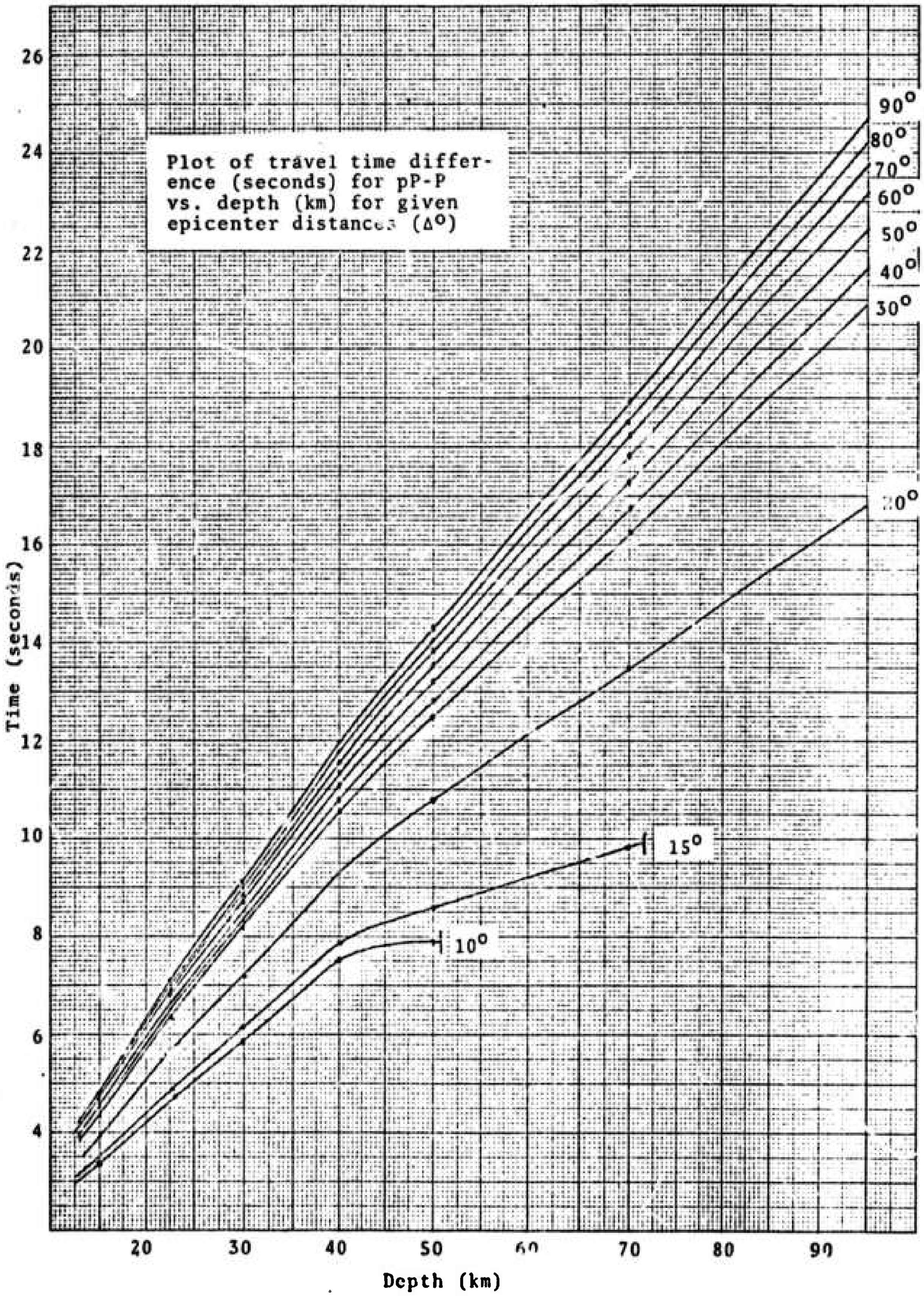
Plot of travel time difference (seconds) for pP-P vs. depth (km) for given epicenter distances (Δ°)
Time (seconds)
Depth (km)
90°
80°
70°
60°
50°
40°
30°
20°
15°
10°
26
24
22
20
18
16
14
12
10
8
6
4
20
30
40
50
60
70
80
90

FIGURE 4

(P↓)P-P: TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	.70451569E+00	-.88319599E-03	-.85335509E-04
J = 1	-.15119426E+00	.18381440E-02	-.78442494E-05
J = 2	.17816886E-01	-.35701656E-03	.31772821E-05
J = 3	-.10480308E-02	.27611793E-04	-.28151927E-06
J = 4	.36120111E-04	-.11502724E-05	.12401366E-07
J = 5	-.77702894E-06	.28589908E-07	-.31769065E-09
J = 6	.10590388E-07	-.43734706E-09	.49528985E-11
J = 7	-.89011917E-10	.40420244E-11	-.46377519E-13
J = 8	.42133363E-12	-.20718337E-13	.24000326E-15
J = 9	-.85973085E-15	.45239568E-16	-.52790138E-18

CALCULATED TRAVEL TIME DIFFERENCE TABLE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	1.103	1.233	1.403	1.538	1.561	1.590	1.616	1.637	1.653	1.673
14.900	3.249	3.474	3.923	4.360	4.439	4.528	4.614	4.677	4.734	4.793
23.000	4.866	5.099	5.753	6.469	6.606	6.744	6.888	6.986	7.085	7.177
30.000	6.081	6.346	7.187	8.164	8.357	8.541	8.738	8.870	9.008	9.130
39.900	7.382	7.850	9.015	10.387	10.671	10.924	11.198	11.382	11.578	11.744
50.000	8.036	9.056	10.678	12.480	12.870	13.198	13.551	13.798	14.051	14.266
70.000	*******	10.405	13.556	16.262	16.891	17.397	17.885	18.296	18.637	18.962
100.000	*******	*******	17.527	21.622	22.670	23.533	24.102	24.906	25.245	25.784

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	.040	-.066	-.038	-.083	-.075	-.072	-.071	-.066	-.066	-.061
14.900	.125	.018	.010	-.008	.001	.002	-.001	.008	.011	.006
23.000	-.141	-.163	-.063	-.090	-.094	-.087	-.091	-.077	-.067	-.075
30.000	-.190	-.184	-.006	-.042	-.053	-.040	-.054	-.044	-.031	-.038
39.900	.156	.031	.305	.199	.156	.183	.145	.165	.173	.164
50.000	-.123	-.461	.069	.014	-.035	.002	-.027	.012	.009	.003
70.000	*******	-.587	-.046	-.009	-.120	-.083	-.087	-.085	-.027	-.053
100.000	*******	*******	.005	.231	-.069	-.082	.082	-.114	.151	.079

FIGURE 5a. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR pP-P

(P+)PP-PP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	.13332966E+01	-.24582721E-01	.47856874E-03
J = 1	-.28393239E+00	.33328531E-02	-.74463907E-04
J = 2	.30372292E-01	-.90408566E-04	.29860351E-05
J = 3	-.18072171E-02	-.59734377E-05	.44096374E-07
J = 4	.65989127E-04	.46604204E-06	-.68787773E-08
J = 5	-.15259838E-05	-.13743890E-07	.23253861E-09
J = 6	.22355513E-07	.21990505E-09	-.40304687E-11
J = 7	-.20078632E-09	-.20139218E-11	.39346127E-13
J = 8	.10079121E-11	.99551033E-14	-.20598689E-15
J = 9	-.21645634E-14	-.20663571E-16	.45130638E-18

CALCULATED TRAVEL TIME DIFFERENCE TABLE (****** MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	1.193	1.070	1.104	1.216	1.406	1.518	1.535	1.559	1.558	1.572
14.900	3.224	3.140	3.261	3.419	3.927	4.293	4.351	4.418	4.428	4.472
23.000	4.652	4.688	4.887	5.012	5.759	6.359	6.457	6.554	6.584	6.656
30.000	5.789	5.844	6.105	6.229	7.196	8.013	8.152	8.271	8.326	8.424
39.900	7.358	7.069	7.397	7.689	9.032	10.173	10.381	10.527	10.628	10.764
50.000	*******	7.665	8.015	8.849	10.711	12.195	12.490	12.658	12.816	12.994
70.000	*******	*******	*******	10.109	13.656	15.823	16.345	16.539	16.837	17.101
100.000	*******	*******	*******	*******	17.859	20.920	21.956	22.157	22.704	23.095

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	-.083	.047	.043	-.055	-.077	-.077	-.081	-.078	-.075	-.069
14.900	.093	.201	.115	.066	.012	-.012	-.007	-.022	.014	.014
23.000	.021	.001	-.156	-.097	-.064	-.094	-.066	-.111	-.073	-.067
30.000	.031	.002	-.201	-.086	-.017	-.048	-.038	-.059	-.024	-.028
39.900	.080	.404	.141	.183	.301	.207	.203	.170	.201	.215
50.000	*******	.102	-.120	-.252	.031	.027	.003	-.004	.013	.022
70.000	*******	*******	*******	-.288	-.141	-.004	-.100	-.130	-.069	-.062
100.000	*******	*******	*******	*******	-.260	.256	-.108	.032	-.101	-.052

FIGURE 5b. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR pPP-PP.

(P↓)PPP-PPP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	-.77633889E+00	.68361173E-01	-.13622038E-02
J = 1	.29864625E+00	-.20124183E-01	.38960040E-03
J = 2	-.34221106E-01	.22266622E-02	-.42768587E-04
J = 3	.20635643E-02	-.12835418E-03	.24445225E-05
J = 4	-.74268357E-04	.44007204E-05	-.82830884E-07
J = 5	.16826877E-05	-.95205747E-07	.17628515E-08
J = 6	-.24211801E-07	.13166893E-08	-.23880077E-10
J = 7	.21451030E-09	-.11306496E-10	.20021912E-12
J = 8	-.10663313E-11	.54928750E-13	-.94807249E-15
J = 9	.22742755E-14	-.11533281E-15	.19392923E-17

CALCULATED TRAVEL TIME DIFFERENCE TABLE

DELTA → DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	1.207	1.173	1.090	1.100	1.194	1.327	1.443	1.485	1.526	1.540
14.900	3.252	3.242	3.210	3.257	3.343	3.639	4.012	4.203	4.321	4.354
23.000	4.679	4.732	4.811	4.390	4.878	5.249	5.862	6.229	6.400	6.447
30.000	5.806	5.911	6.022	6.117	6.034	6.458	7.302	7.851	8.067	8.124
39.900	7.345	7.465	7.342	7.423	7.384	7.913	9.125	9.965	10.248	10.319
50.000	*******	*******	*******	8.055	8.399	9.135	10.778	11.938	12.301	12.386
70.000	*******	*******	*******	*******	9.250	10.975	13.656	15.436	16.028	16.146
100.000	*******	*******	*******	*******	*******	13.039	17.815	20.191	21.429	21.635

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	-.080	-.073	.032	.052	-.052	-.122	-.118	-.068	-.072	-.088
14.900	.087	.063	.120	.119	.059	-.027	.012	.011	.010	-.005
23.000	-.003	-.064	-.138	-.155	-.097	-.120	-.052	-.096	-.060	-.074
30.000	.012	-.100	-.197	-.215	-.064	-.025	-.078	-.060	-.002	-.018
39.900	.069	-.049	.113	.126	.270	.351	.185	.151	.251	.258
50.000	*******	*******	*******	-.173	-.236	.067	-.035	-.059	.093	.103
70.000	*******	*******	*******	*******	-.210	-.002	-.130	-.133	.063	.019
100.000	*******	*******	*******	*******	*******	.430	-.201	-.144	.173	.191

FIGURE 5c. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR pPPP-PPP

(P+)PCP-PCP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	.43430116E+00	-.39806067E-02	.26096260E-04
J = 1	-.14028699E-01	.72844103E-03	-.55860908E-05
J = 2	.14257720E-02	-.78747384E-04	.59120923E-06
J = 3	-.71953567E-04	.43250873E-05	-.31612775E-07
J = 4	.19617897E-05	-.13472496E-06	.94863732E-09
J = 5	-.28743273E-07	.24805786E-08	-.16505101E-10
J = 6	.18608325E-09	-.26787129E-10	.16162892E-12
J = 7	.25233836E-12	.15802061E-12	-.76825728E-15
J = 8	-.97609346E-14	-.40814595E-15	.70592439E-18
J = 9	.36591970E-16	.12450430E-18	.45708095E-20

CALCULATED TRAVEL TIME DIFFERENCE TABLE (****** MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.00	1.724	1.723	1.726	1.715	1.703	1.699	1.691	1.679	1.682	1.683
14.90	4.953	4.947	4.948	4.921	4.887	4.870	4.848	4.819	4.821	4.823
23.00	7.431	7.419	7.413	7.376	7.325	7.293	7.263	7.224	7.219	7.221
30.00	9.469	9.449	9.434	9.392	9.326	9.279	9.243	9.198	9.184	9.185
39.90	12.210	12.179	12.148	12.099	12.013	11.942	11.900	11.846	11.817	11.817
50.00	14.860	14.825	14.777	14.720	14.613	14.516	14.469	14.404	14.358	14.356
70.00	19.862	19.788	19.716	19.637	19.477	19.338	19.274	19.172	19.099	19.094
100.00	27.187	27.073	27.028	26.864	26.583	26.432	26.306	26.075	26.012	26.007

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.00	-.059	-.058	-.066	-.063	-.057	-.064	-.056	-.049	-.058	-.050
14.90	.009	.007	-.004	-.001	.010	-.000	.009	.024	.019	.016
23.00	-.072	-.070	-.080	-.080	-.071	-.077	-.079	-.061	-.071	-.079
30.00	-.038	-.034	-.041	-.048	-.040	-.043	-.049	-.035	-.036	-.048
39.90	.149	.158	.161	.144	.154	.151	.145	.158	.168	.165
50.00	-.003	.013	.021	-.014	-.005	-.002	-.027	-.009	.005	-.002
70.00	-.056	-.024	-.097	-.068	-.051	-.076	-.092	.005	-.042	-.054
100.00	.008	.058	.019	-.023	.038	-.014	-.050	.064	.058	.024

FIGURE 5d. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR pPcP-PcP

Each differential travel time surface considered in this work, except those representing core reflections, exhibit an unallowed region, i.e., there exists a range of epicenter distances for which below a certain depth the surface reflected mode is not received. The boundary of such a region projected into the (d,Δ) plane for pP-P is shown in Figure 6.

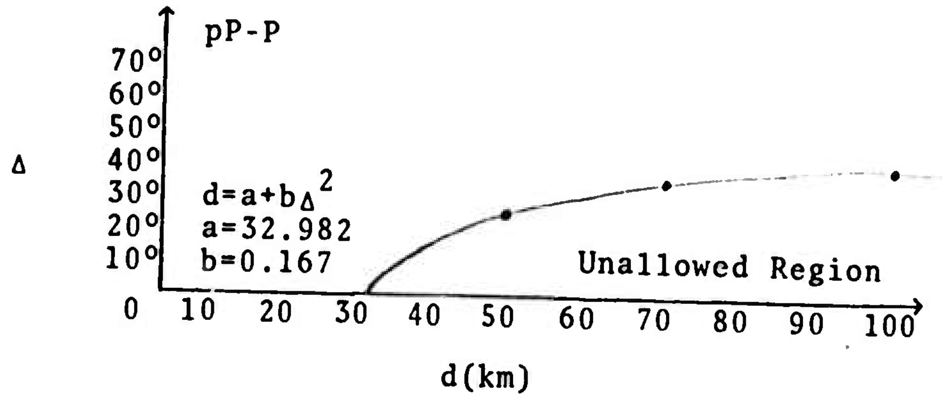

FIGURE 6

These boundaries can be adequately represented by a parabola so that our polynomial model is subject to the constraint that for a given Δ we must have $d < a+b\Delta^2$, where a and b have been determined from least square adjustments to plots like that of Figure 6. In Figure 5, the unallowed region is shown as asterisk table entries.

Case II: Line Fits to PP-P, PPP-P, PcP-P

These travel time difference plots can be represented as single curves depending on Δ only, since between 5 and 100 km, the depth dependence is very weak. Thus we have

$$\tau(d,\Delta) = \tau_o(\Delta) = \sum_{j=o} \tau_{oj}\Delta^j .$$

The PP-P and PPP-P differences appear to vanish as $\Delta \to o$, so for these surves we set $\tau_{oo} = 0$ and also find N=8 is sufficient. For PcP-P, the core reflection insures that $\tau_{oo} \neq 0$. Here N=6 is sufficient.

This polynomial surface representation of the differential travel times can be stored using a total of 143 coefficients and requires less than .02 seconds to compute these times for eight propagation modes on the CDC 6600 computer.

Future Plans

A prototype of the automated seismic source depth analysis procedure has been developed and applied to the first minute of the seismograms recorded for the Illinois Event. During the next quarter we will apply this analysis to succeeding data in which the propagation modes PP,PPP and PcP are present. We will investigate the effectiveness of this analysis in enabling constructive use of the depth phase information and to determine what modifications may be necessary. We will also investigate, through the application of this analysis to additional events, those modifications necessary to enhance the statistical significance and resolution of these source depth estimates. During this period, we will also begin to investigate the usefulness of the Maximum Entropy techniques in extending the applicability of the analysis procedures to shallow events.